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Experimental Observation of Plasma Formation and Current Transfer in Fine Wire Expansion Experiments

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Experimental Observation of Plasma Formation and Current Transfer in Fine Wire Expansion Experiments

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Abstract

When several kA pulses are passed through single, fine 25 μm diameter wires, the wire material heats, melts, vaporizes and expands. Initially the voltage across – and current through – a wire increases until an abrupt voltage collapse occurs. After this collapse the voltage remains at a relative small value while the current continues to increase. In order to understand how this early time behavior may affect the subsequent implosion, small-scale experiments at Cornell University's Laboratory of Plasma Studies concentrated on diagnosing expanding single wire dynamics. X-ray backlighting, interferometry and Schlieren imaging as well as current and voltage measurements have been employed. The voltage collapse has been attributed to the formation of plasma around the wire and a transfer of current to this highly conducting coronal plasma. Interferometry has confirmed the plasma formation, but the current transfer has only been postulated. Subsequent experiments on the Z-Facility at Sandia National Laboratories have produced impressive x-ray yields…. etc.

Acknowledgment

We would like to thank the support of Gerry Yonas as the Cornell University point-of-contact, and many of the staff in the pulsed power center of Sandia National Laboratories

Contents

Figures

Background

The LDRD Project involved experimental measurements of 25 μm, single wire explosions driven by ~ 100 ns current pulses during the low current (i.e., several kAmp) expansion phase. The measurements can be broken down into two categories: spectral observation of the emitted light and direct observations of the transfer of current from the wire core to the surrounding plasma, and can be found in Appendix A.

Experiments on the Z-Facility at Sandia National Laboratories with current driven imploding cylindrical wire arrays have produced impressive x-ray yields [1, 2]. Before the magnetic pressure is large enough to cause implosion the individual wires melt, vaporize and expand [3,4].

During the expansion phase, while the currents through and voltage across the wire are increasing, a sudden voltage collapse occurs. After this collapse the voltage remains relatively small while the current continues to increase. This voltage collapse has been attributed to a plasma discharge forming around the partially vaporized wire, and a transfer of current from the neutral wire material to the plasma has been postulated.

Interferometry measurements at 532 nm have observed a 2×10^{19} cm^{-3} plasma shell surrounding a neutral core during and after voltage collapse[5,6]. Details of the dynamics of the plasma formation and current transfer from the neutral wire material to the highly conducting plasma are not well understood and have been explored via the following experiments.

Body

Single, 3 cm long, 25 μm diameter copper wires were driven by a 75 nF capacitor charged to approximately 15 kV. An inductive circuit connected a single wire in series with the capacitor. The circuit parameters were adjusted to give a 15 A/ns current risetime, similar to the pre-pulse on the large Z-machine at Sandia. All the experiments were conducted in a vacuum with the background pressure less than 5×10^{-5} Torr. The observed current, inductively corrected voltage, and resistance of a wire as functions of time are shown in Figure 1.

The resistance was obtained from the corrected voltage and total current. Initially the wire had a cold resistance of 2 **Ω**. When it was ohmically heated, resistance increased. At 75 ns it reached a value of 16 **Ω**, whereupon the voltage collapse occurred and resistance fell to less than 0.3 **Ω**. The collapse took only a few nanoseconds.

To confirm the presence of plasma during and after voltage collapse, time-resolved measurements of the emitted light were made. A vacuum photodiode and a framing camera produced the best results. To prevent saturation the photocathode of the vacuum photodiode was biased to –2000 V with respect to the anode mesh. With filters, we determined that the photodiode was responding to ultraviolet light. The response time of the photodiode was < 1 ns, thus the ~8 ns risetime of the photodiode signal shown in Figure 1 is a real effect. After voltage collapse, low level UV radiation was observed for the remainder of the current pulse. The timing of the voltage collapse was coincident with the risetime portion of the UV light. The four signals in Figure 1 were synchronized to better than half a nanosecond and are typical of several single-wire shots.

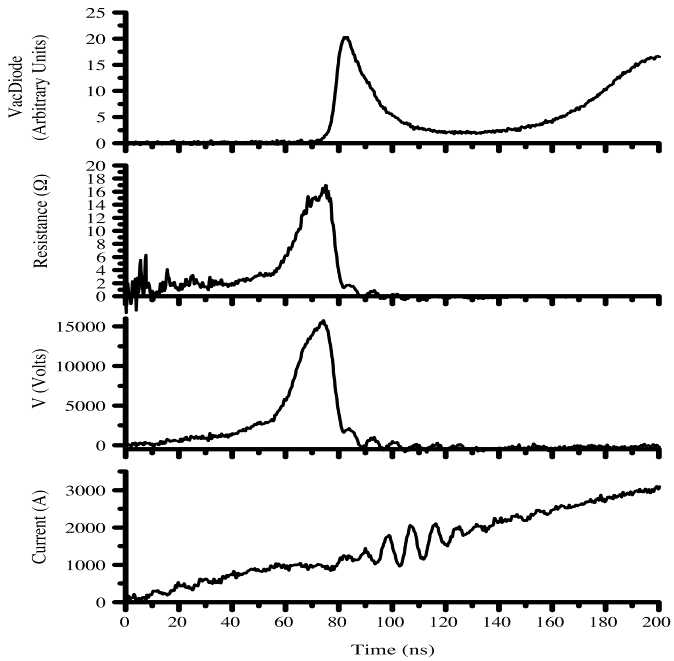
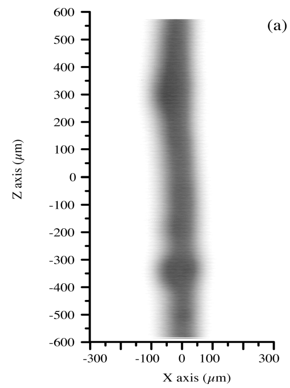


Figure 1: Some properties of a 25 μm diameter, 3 cm long wire when being pulsed with current. Current, Voltage, and Resistance refer to the electrical characteristics of the wire and plasma surrounding the wire. Vacuum Diode refers to the response of a vacuum photodiode that was looking at the wire during the pulse.

In order to estimate the volume of plasma surrounding the wire at the time of voltage collapse, a framing camera imaged the emitted visible light. Figure 2a shows a picture taken while the voltage was collapsing. The camera's 8 ns shutter opened 74 ns into the current pulse. Figure 2b shows the pixel intensity as a function of the distance x in the picture averaged over several horizontal lines of the image. The scale in the picture shows that at this time the plasma extended over a diameter of at least 310 μm. It should be noted that these measurements indicated plasma extending to a much larger radius than was detectable by the less sensitive 532 nm interferometer[7].



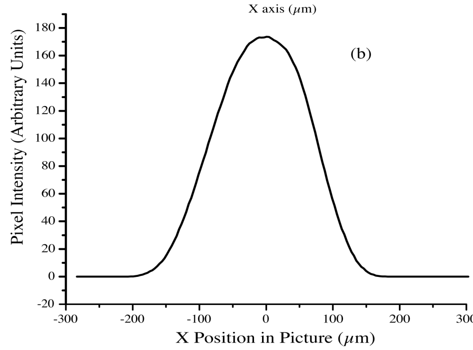


Figure 2a: A picture of the plasma surrounding the exploding wire taken by a framing camera. The camera responds to visible light and had a shutter that stayed open for 8 ns. This picture was taken when the voltage along the wire started to collapse, about 75 ns after the current started.

Figure 2b: The intensity of the pixels of Figure 2a as a function of x. This distribution was found by averaging over several horizontal lines of the picture. It shows that the framing camera detected a column of plasma around the wire that was 310 μm wide

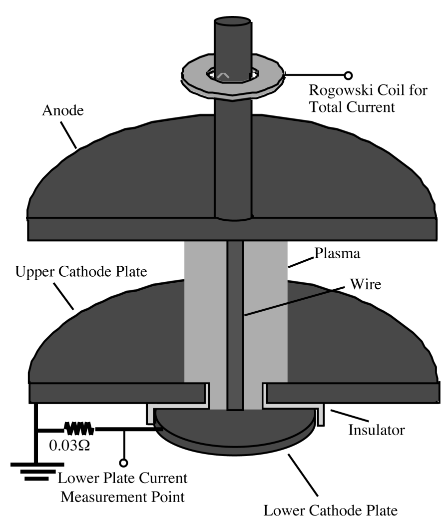


Figure 3: The new wire holder that measures current conducted by plasma at distances from the center of the wire. The resistor provided a way of measuring the current through the bottom plate while the Rogowski coil provided a measurement of the total current through both the plasma and wire.

After confirming the existence of plasma formed around the exploding wire at the time of the voltage collapse, attention turned to the details of the current flow and the question of current transfer to the surrounding plasma from the neutral wire material at the core. To accomplish this, a new, grounded cathode for the wire holder was constructed (Figure 3). The new cathode consisted of two stacked plates separated by insulation. The upper plate contained a hole 740 µm in diameter and lined with insulation 130 µm thick. After passing through this hole the wire was attached to the bottom plate. The top plate was directly grounded and the bottom plate was grounded through a 0.03 Ω shunt resistor. The voltage across this current shunt measured the current flowing to the bottom plate. An external Rogowski coil measured the total current that flowed to the anode plate and then through both the plasma and wire. The current conducted by the top cathode plate was obtained by subtracting the bottom plate current from the total current.

The underlying expectation of this experiment was that if current flowed through the wire core or plasma near this core, it would be collected by the bottom plate. If current flowed through plasma far enough away from the wire core, it would be collected by the upper plate. Figure 5 shows a set of results from this experiment. Initially the bottom plate collected all the current. While the voltage was collapsing, the current appeared to split between the upper and lower plates, and eventually no current flowed to the bottom plate.

It should be noted that the wire was probably not perfectly centered in the 740 µm, upper cathode plate hole. The edge of the wire could have been close to the edge of the larger hole in the upper plate, touching the insulation around the upper hole. If so, the plasma would only have needed to extend 130 µm from the edge of the wire core to be in contact with the upper cathode plate. If the wire were perfectly centered the plasma would need to extend 370 µm from the edge of the wire before current could transfer. Either way, Figure 4 shows that current was eventually conducted at significant distances from the center of the exploding wire.

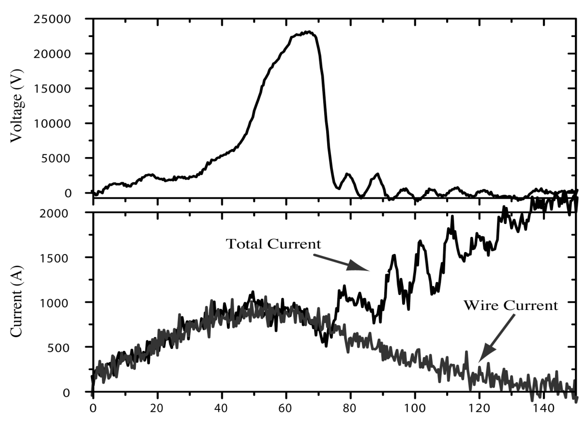


Figure 4: The transfer of current from the wire to the plasma. The bottom plate signal represents the current that was flowing through the wire and the plasma close to the wire. All of the current was flowing through the bottom plate until the time of voltage breakdown. After that point, less current was flowing through the lower plate, which indicates that plasma was making contact to the upper plate and conducting most of the current.

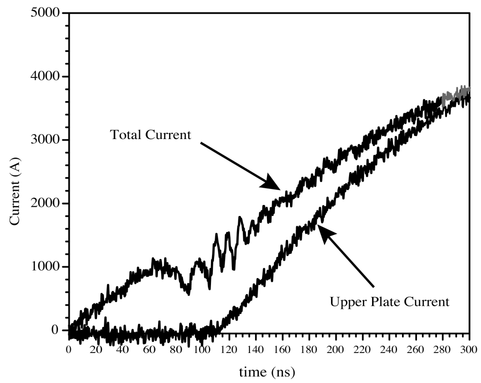


Figure 5: The transfer of current when the hole was enlarged. In this case the hole in the upper plate was enlarged to 1400 μm and the resistor was moved so that it could monitor the current through the upper plate. Current did not start flowing through the upper plate until 40 ns after the voltage collapsed.

A second configuration of the cathode plates was investigated. The hole diameter in the upper plate was increased to 1400 μm to see if this would delay the time the upper plate began collecting current. The idea was to enlarge this hole to ensure that plasma would not be in contact with the upper plate until well after voltage collapse. In addition, the shunt resistor used to measure current flow was moved from the bottom plate to the upper plate to lessen the impedance mismatch of the two cathode circuits. Figure 5 shows the results of this experiment. In this graph the upper trace is still the total current and the lower trace shows the current that flowed through the upper plate. No current flowed through this plate until 40 ns after the voltage collapsed. Assuming the plasma formed at voltage collapse initially, it did not extend radially far enough to make electrical contact with the upper plate. After the current started to flow in the upper plate, it took another 40 ns before it collected half the current. Almost all the current was conducted in the upper plate for times greater than 300 ns. These measurements allowed the plasma expansion velocity to have an estimated lower velocity of 14 μm/ns**,** which is more than the 2.5 μm/ns velocity measured by laser interferometry[7].

Figures 4 and 5 warrant some additional comments. First, the oscillations present on the total current signal just after voltage collapse appear to be a result of the driving circuit and not associated with the physics of the current transfer. The response times of the Rogowski monitor and current shunt were measured by driving them with a known pulse with a risetime < 2ns. The response time of the Rogowski was < 10 ns and that of the current shunt was <250 ns but > 50 ns. Consequently while the Rogowski monitor detected 9 ns oscillations, the current shunt was insensitive to them. These oscillations appear to be the result of a resonance resulting from the inductance of the driving circuit combined with the capacitive vacuum feed through. When the driving circuit inductance and/or the capacitance of the feed through decreases the frequency of these oscillations increases.

Second, the delay in the time it takes for the current to completely transfer to the upper plate may be real or may be introduced by the diagnostics. It is not unreasonable that there be a real delay in the transfer caused by the inductances of the wire core and the plasma paths coupled with the plasma conductivity. This delay would be associated with the time it takes for the magnetic field to diffuse through the plasma, and could be used to verify computer simulations.

However, the diagnostics could also be introducing a delay. The resistive shunt circuit used to measure the current has an inductance of its own and a decaying current could circulate between the upper and lower cathode plates, resulting in an observed current in the shunt not really flowing in the wire core or coronal plasma. In addition, because the size of the hole in the top plate was larger than the wire cross-section, some plasma current was collected by the lower plate. As time increases and the plasma expands, the percentage of the plasma current flowing to the lower cathode plate will decrease. It is quite likely that all of these effects are present and that the real transfer time is not instantaneous but also not as long as the data in Figures 4 and 5 would imply.

Summary

In summary the results show that the plasma generated after voltage collapse extends to a larger radius than was observed and reported by the 532 nm interferometry. In addition, the first direct, experimental observations of the transfer of current from the wire core to the coronal plasma have been presented.

References

[1] R.B. Spielman, C. Deeney, G.A. Chandler *et al*., in *Physics of Plasmas* **5**, 2105 (1998).

[2] T.W.L.Sanford, R.E.Olson, R.C. Mock *el al*., in *Physics of Plasmas* **7**, 4669 (2000).

[3] D.B. Sinars, T.A. Shelkovenko, S.A. Pikuz, Min Hu, in *Physics of Plasmas* **7**, (2000).

[4] D.B. Sinars, Min Hu, K.M. Chandler *et al.*, in *Physics of Plasmas* **8**, 216 (2001).

[5] D.B. Sinars, T.A. Shelkovenko, S.A. Pikuz, Min Hu, V.M. Romanova, K.M. Chandler, J.B. Greenly, D.A. Hammer and B.R. Kusse, Physics of Plasmas, 7, 429 (2000).

[6] D.B. Sinars, Min Hu, K.M. Chandler, T.A. Shelkovenko, S.A. Pikuz, J.B. Greenly, D.A. Hammer and B.R. Kusse, Physics of Plasmas, 8, 216 (2001).

[7] B.R Kusse, Min Hu, P.U. Duselis, K.M. Chandler and D.A.Hammer, Proceedings of the 14th International Conference on High-Power Particle Beams and 5th International Conference on Dense Z-Pinches, Alburquerque, NM, June, 2002.

Appendix A:

Two Categories of Measurements of Single Wire Explosions (originally reported in a paper for Sandia LDRD Project 02-1465, September20, 2002)

Spectral Measurements

For one set of experiments spectral measurements of the light emitted by 25 micron copper and molybdenum wires were recorded for current pulses with two different risetimes, 15 A/ns to simulate the prepulse risetime on Z, and a faster 90 A/ns risetime.

Typical time-integrated spectra of the light emitted are shown in Figure 1. Both types of pulse produce a voltage collapse which occurs for the slower pulse at ~70 nsec and for the faster pulse at 50 nsec. Approximately twice the energy was deposited in the wires before voltage collapse by the faster pulses as compared to that deposited by the slower pulses. As shown in Figure 1 the emission generated by the slower pulse was dominated by line radiation while the faster pulse produced a continuous, possibly black-body-type spectrum. The lines in the discrete spectra occurred at wavelengths characteristic of neutral copper or molybdenum. In addition, lines appeared that may be due to impurities like oxygen and nitrogen but further work needs to be done to better understand the spectra. The continuous spectra produced by copper and molybdenum wires driven by fast pulses were essentially identical and at a higher intensity than the line spectra resulting from the slower pulses. The faster pulses deposited about twice as much energy in the wires before voltage collapse than the slower ones and it is possible that the line spectra were also present in the fast pulse spectra but were overpowered by the continuous emission.

Another set of spectral measurements was made to compare the performance of wires preheated before application of the current pulses with that of wires that were not preheated. Molybdenum and Tungsten wires, both 25 μm wires were preheated in vacuum by a 170-250 mA current. Two preheating times were used, 1/2 hour and 8 hours. Two different situations for the kA pulses were used. In one case the pulse was applied 30 seconds after the heating pulse was turned off, and in the other the pulse was applied while the heating current was still flowing. Typical results are shown in Figure 2. The preheated Molybdenum wires showed lower amplitude line radiation, implying that the impurities had been reduced. For the tungsten wires the preheating appeared to make little if any difference in the emitted spectrum.

Work on these spectral measurements is continuing and the discussion above is only a summary of the results to date. Additional measurements on the effects of preheating, pulse risetime and wire material will be made along with a more detailed analysis and interpretation of the spectra.

Observations of Current Transfer From the Wire Core to a Surrounding Plasma

A holder for single wires splits the current in the exploding wire channel into two parts, flowing inside and outside of a specified radius (as measured from the center of the wire. Before voltage collapse the current flowed in the wire core. After voltage collapse the current gradually transferred to a plasma (generated at voltage collapse) and surrounded the wire core. The timing onset of the plasma was confirmed by framing camera images of the emitted light.

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